EFFECT OF EXPANSION ON COLLAPSE AND BURST STRENGTHS OF SOLID EXPANDABLE TUBULAR

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ABSTRACT

Pipes or tubulars are subjected to expansion processes in large variety of engineering applications spanning full spectrum of industries such as automotive, aerospace, oil and gas, etc. One such application is its use in design of oil and gas wells. Tubulars or pipes of various diameters and wall thicknesses are subjected to full length expansion during the construction of oil and gas wells based on design requirements in order to conserve the hole sizes to reach maximum depth within the formation to tap oils from difficult reservoirs. However, due to the different layers of formations, stability and fluidity of formations across the depth pose various challenges to complete the drilling and completion of oil and gas wells. Two such major challenges come across due to the failure of pipes either due to burst or collapse, which are caused by sudden or gradual increase of internal or external pressure to the pipes. Additionally, the paradigm shift in design from conventional wells to slim wells utilizes in-situ expansion of pipes, which results not only change in pipe dimensions but also have detrimental effect on its collapse and burst strengths. In this work, experimental works are done to expand steel pipe LSX80 under different conditions. Burst and collapse strengths of expangggggggggggggded pipes are determined to estimate the change in strengths due to expansion process. Good agreements are found between experimentally data and analytically determined values. It is found that the burst strength decreases in the range of 20% of its original strength value as a result of expansion process. Major decrease in collapse strength (approximately 40% to 50% decrease) is observed due to expansion, which means the pipes will become vulnerable to failure due to formation movement. Hence, a prior knowledge of its strengths after expansion will lead designers to design wells accordingly to avoid failure during its operational life.

1. INTRODUCTION

In next few decades, the energy consumption of oil-based products is expected to increase between 2-3% annually, which require substantial efforts to meet this energy demand. With significant growth and cost reduction in renewable energy sources, the oil and gas operators face two major challenges. First, extraction of resources from reservoirs which are difficult to reach and drill. Second, to reduce the cost of drilling, completion and later repair and maintenance of drilled oil and gas wells. Both these challenges require technological development that can allow to drill difficult and deeper reservoirs with smaller well diameter, and that results in less tubular material, less drilling fluids, less drill cutting disposal, less cement and shorter time period to drill and produce while maintaining the smoothness and stability of the well-bore [1]. The use of Solid Expandable Tubular (SET) technology reduces the casing to just fit for the required hole size at total depth with a saving of 20% to 40% of the total cost. For instance, oil-well drilling starts with surface hole size of 36” diameter then reduction will follow as we drill deeper. Whereas by using SET technology the surface hole size would be 9.625” to 14” and reduction will follow afterwards. In most of the published references, SET is defined as a down hole cold work process to expand a tubular to certain diameter. In general, the expansion process is achieved by placing a mandrel or cone inside the tubular, and by the push or pull force the cone moves forward and expands the tubular to desired diameter.

A review of selected literature on down-hole tubular expansion [2-3] shows that most of the research and development work were aimed to find quick solution to specific problems. On the other hand, simplified to complex analytical solutions [4-5] were obtained by taking into account of material and contact nonlinearities present in the system during down-hole expansion process in which the stress field in the expansion zone, expansion force, and dissipated energy were predicted in order optimize the expansion process. The reliability and structural integrity of tubulars after expansion depends on post expansion tubular material properties and is important due to the necessity that the oil-well tubular must withstand all loads generated either by the formation or by the drilling operation itself. In this context, research has focused upon developing semi-analytical solutions, finite element simulations and experimental works. The capacity of the research has been strengthened with the design, fabrication and commissioning of SET test setup at Sultan Qaboos University, which is capable of conducting tubular expansion of varying diameters and lengths by mimicking actual down-hole conditions. Many essential SET-related research work were done including; simulation of tubular expansion using the finite element method to study the effects of different expansion ratios, friction coefficients and mandrel angles on the tubular expansion process [6]; analytical model of wave propagation due to the pop-out phenomenon [7]; dynamic effects of mandrel-tubular interaction in the down-hole tubular expansion process [8]; experimental and numerical investigation of expandable tubular structural integrity for well applications [9] to name a few.

An important issue which still has not been thoroughly understood is the effect of loading/boundary conditions on tubular’s strength parameters and ultimately its structural integrity. These conditions sometimes have resulted in undesirable geometrical and behavioral changes in the tubular during the expansion process which may lead to premature failure of the SET during its lifetime. A close look at the expansion process, supported by experimental data, showed that these failures may occur due to unfavorable thickness variations during the expansion process. The successful expansion process must ensure that the expanded tubular bears no fracture/burst or any other damages and have constant tubular diameter along its length. From materials point of view, the phase changes alter mechanical properties such as toughness, tensile properties, corrosion resistance, connection integrity, etc. One critical issue is related to stick-slip phenomenon, which happens when the cone sticks during the expansion process due to inadequate lubrication, the presence of irregular tubular surface caused and slips when excessive force build up on the cone. It causes undesirable variations in wall thickness of tubular, which results in lowering of tubular collapse and burst strengths after expansion and has significant bearing on operational issues and life span of expanded tubular. In view of the discussion above, the objective of this work was to conduct a study to investigate the collapse and burst strengths of the tubular after expansion.

2. EXPERIMENTAL AND ANALYTICAL PROCEDURE

In this research, standard SETs used in oil/gas wells were expanded via a cone placed at one end of the tubular. A hydraulic pressure build-up at the end of the cone pushed it forward to expand the tubular under two different boundary conditions i.e. fixed-free and fixed-fixed. In down-hole applications, the tubular is usually run through an existing casing string and deployed to a specific depth with the cone attached to it. Once the system is positioned in an open-hole or inside previous casing, it is anchored in place by fixing one of its ends. The anchoring is usually done against the formation in open-hole applications such as expandable open-hole liners or against another tubular in cased-hole applications such as expandable casing clads. In order to obtain necessary data to perform the experiment, the test-rig is provided with proper instrumentation to monitor, control, and store information related to principal variables. Parameters recorded during the test include strain, diametrical displacement, expansion force, wall thickness and length variations, operating fluid temperature, flow rate, and the speed and location of the expansion cone. Several electronic pressure sensors were used to measure the hydraulic pressure supplied to the cone-tubular system, and an ultrasonic sensor was employed to monitor the cone position as it moved along the tubular during the expansion process. The variation in outside diameter was precisely measured through a linear voltage displacement transducer (LVDT), which was selectively installed on opposing sides of the pipe (0-180°). The variation in pre- and post-expansion wall thickness was measured by using a TI-25DL ultrasonic wall thickness gauge at five different locations on the outer surface of the pipe (Pi, i = 0, 1, 2, 3, 4) following a 0 and 180-degree pattern as shown in Figure 1. The method utilized to quantify the change in length was to draw straight lines of known lengths (L_1 and L_2) along the outer surface of the pipe before the expansion process. Posterior to mechanical expansion, the length was re-measured, indicating the variation caused by the cold forming process. Based on whether the bottom section (front-end in Fig. 1), the top section (rear-end in Fig. 1), or both of them happened to be fixed during tubular expansion applications. Out of many possibilities for expansion, in this work the tubular is expanded under (a) tension when the bottom section (front end) is fixed and the top section (rear end) is free, and (b) compression when the front end is free while the rear end is fixed.

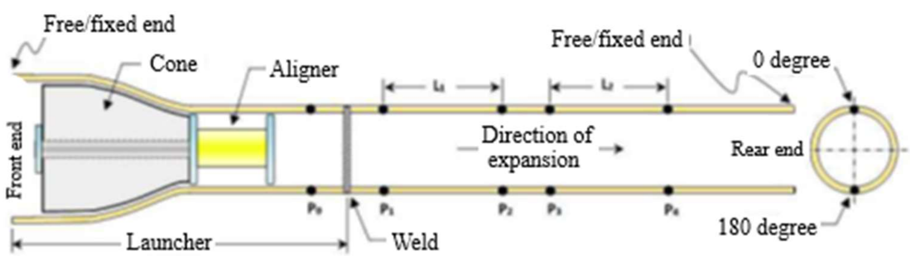

Figure 1: Schematic diagram of the expandable tubular test setup

The nominal internal pressure rating (burst rating) of tubular is calculated by using the American Petroleum Institute (API) equation or Barlow Equation. This equation is one-dimensional representation of the von Mises condition in association with a fairly accurate expression of the hoop stress in the pipe body. The Barlow's equation, which is less accurate than Lame's for thin wall tubular and neglects the axial stress, approximates the hoop stress to match it with the yield strength of the tubular body. In other words, the initial yield pressure of a thin tubular body $P_{iY\text{ - }API}$ is defined as:

$$P_{iY\text{ - }API} = (0.875*2*\sigma_{Yield}*t)/D$$

where σ_{Yield} is the minimum nominal yield strength, t is the tubular wall thickness, D is the tubular diameter, and 0.875 is the factor to account the manufacturing tolerance of the tubular wall specified by API standards. Current tendencies within the industry suggest that the most accurate calculation method of the designed yield pressure of oil and gas tubulars is through the criterion proposed by von Mises. The triaxial tubular body yield combines a diverse number of equations, such a Lame's for thick cylinder, Timoshenko's for bending stress, as well as uniform axial stress (independent from bending) and torsional shear stress. Based upon the triaxial principle, the initial yield of the tubular body occurs when the stress applied in its working environment reaches the equivalent von Mises stress. For the special case of purely internal pressure, when external pressure, axial load, bending and torsion are zero, the internal pressure at yield for an open-end thick tubular is:

$$P_{iY} = [\sigma_{Yield}*(D^2 - d^2_{wall})] / \{(D^4 - d^4_{wall})\}^{0.5}$$

where d_{wall} = D-2(0.875)*t, D is specified outside tubular diameter and t is the wall thickness.

In terms of collapse strength, the D/t value of pre-expansion tubular corresponds to the range for plastic collapse (Table 6, ISO 10400) [10]. However, once the tubular is expanded both D and t are notably modified to the point where, by assuming the same conventional material yield strength, the collapse behavior becomes transitional (Table 7, ISO 10400) [10]. Nevertheless, unpublished data suggests that even the σ_{Yield} is also different after expansion, mainly due to the cold work process. In order to consider other published research works, the authors assumed that the variation of σ_{Yield} ranges from -15% to +15%. This range transforms the SET material into either a potential C70 or C90 material (nomenclature used by ISO 10400). In both cases, the collapse equation corresponds to the transition zone; but the nominal minimum yield strength varies and affects both the overall collapse and burst pressure calculations. It is important to note that the after-expansion properties of the tubular must be suitable to withstand all loads during different stages of the drilling, installation and production processes. Consequently, both the internal pressure/yield and the collapse pressure are calculated using the post-expansion dimensions and final minimum yield strength.

3. RESULTS AND DISCUSSION

Two tubulars of internal diameters of 193.6 mm (wall thickness 9.53mm) and 203.2 mm (wall thickness of 10.2mm) were expanded using a 10-degree angle cone pushed by hydraulic pressure generated by high pressure pump working at a flow rate of 50 liters/minute. The tubular is made of high strength, low-alloy steel with 0.23% carbon, 1.34% manganese, 0.23% silicon, 0.011% phosphorus, and 0.002% sulfur with yield strength of 620 MPa and ultimate tensile strength of 715 MPa.

Table 1 summarizes the results obtained through experiment of both tubular types including the force required for expansion, length shortening and reduction in tubular wall thickness. Two end conditions are used in conducting experiments as mentioned before. The reduction in wall thickness of two tubulars, under fixed-free end condition, is approximately 9% and 11.92%, respectively, while the length shortening is 43.8mm/m and 49.2mm/m, respectively. Similarly, the reduction in wall thickness of 203.2 diameter tubular under fixed-fixed end condition is 14.2% and change in length is 7.45mm/m. Although there should be no change in length due to fixed-fixed end condition, but the change took place once the fixed end is removed after assuming that steady conditions were achieved. From an operational point of view, positioning the expandable pipe at the planned depth inside the well-bore is extremely difficult and accordingly may be positioned somewhat higher than where it was supposed to be. Such wrong positioning of the tubular without adequate information about the degree of the effect of the expansion on the length shortening would affect the anchoring of the fixed-end of the tubular, causing inadequate coverage of difficult areas.

Table 1: Experimental results of two tubular sizes expanded under two end-conditions using cones of 203.2 mm and 218.44 mm diameters

Tubular Diameter x t	Cone Size	End Condition	Change in Length	Change in Wall Thickness
193.68 x 9.53 mm	203.20 mm	Fixed-Free	43.80 mm/m	8.00 %
203.20 x 12.7 mm	218.44 mm	Fixed-Free	49.20 mm/m	12.30 %
203.20 x 12.7 mm	218.44 mm	Fixed-Fixed	*7.45 mm/m	14.20 %

* It should be zero but change occurred once fixed end was released at one end after 12 hours of experiment.

As shown in Table 1, the 203.2 mm inner diameter tubular with 17.2% enlargement in its outer diameter experienced 12.3% reduction in wall thickness. Two fundamental limits of yield strength is of importance, which are the internal pressure that can be withstood by a tubular at the onset of yielding of the inner surface, and the internal pressure required to cause the whole wall to yield completely. Thus, after performing the expansion process, a tubular sample of one meter in length was cut and the edges were chamfered. Afterwards, flanges were welded on both sides of the pipe, producing a chamber-type system and experiment was conducted to determine these two internal yield pressures. The test confirmed yield strength variation in a range of ±15%. The ratio of outer diameter to wall thickness (OD/t), outer diameter (OD) and the minimum yield strength (σ_{Yield}) of expanded tubular have detrimental effect on its burst and collapse ratings, in terms of units of pressure. Now, using the geometrical parameters of the SET sample along with the standard API formulations given above for burst rating and ISO 10400 standard for collapse rating, calculations are done and summarized in Table 2, which describe the full effect of D/t changes on burst and collapse design calculations. The major effect on tubular's burst and collapse rating is generated by the OD/t ratio, in a larger magnitude than the variation of the minimum yield strength. Similar conclusions are obtained by the unpublished data provided by manufacturer as a result of physical collapse tests conducted on only one set of samples.

Table 2: Effect of cold expansion on burst and collapse ratings of tubular using API and ISO-10400 standard design equations

Tubular Diameter x t (API Spec.)	**OD/t**	**Min. Yield Strengths** (Bar)	**Burst Rating** (Bar)		**Collapse Rating** (Bar)	
			Pre-expansion	Post-expansion	Pre-expansion	Post-expansion
203.2 x 12.7 mm (SET-LX-80)	16.00	5515.80	598.74	-	556.00	-
203.2 x 12.7 mm (SET-LX-80)	21.36	4688.43	-	382.52	-	271.58
203.2 x 12.7 mm (SET-LX-80)	21.36	6343.18	-	517.52	-	305.30

4. CONCLUSION

The research work aimed to study the effect of cold expansion under down-hole conditions on burst and collapse ratings of solid expandable tubular. API and ISO-10400 standards design equation were used to calculate the burst and collapse pressures before and after expansion based on obtained experimental data. Investigating the effect of end-conditions on the tubular structural integrity showed that the difference between expanding the tubular under tension (fixed-free) and expanding it under compression (Fixed-fixed) is very minor and can be ignored. Tubular expansion under fixed-fixed end-condition resulted in a larger wall thickness reduction, hence more pronounced effect on collapse rating after expansion. Simple calculations suggest that the wall thickness reduction along with the enlargement of external diameter (OD/t ratio) causes a much larger and valuable effect on post-expansion collapse rating as compared to burst. It was found that the end-conditions had minor effect on the yield limit of the tubular.

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